Study of VHF deposition of nc-Si:H solar cells

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Research motivations:

1. **nc-Si:H cells as alternative for a-SiGe:H bottom cells in multi-junction a-Si:H based solar cells.**

2. **Necessary high deposition rate for nc-Si:H i-layer using VHF PECVD.**

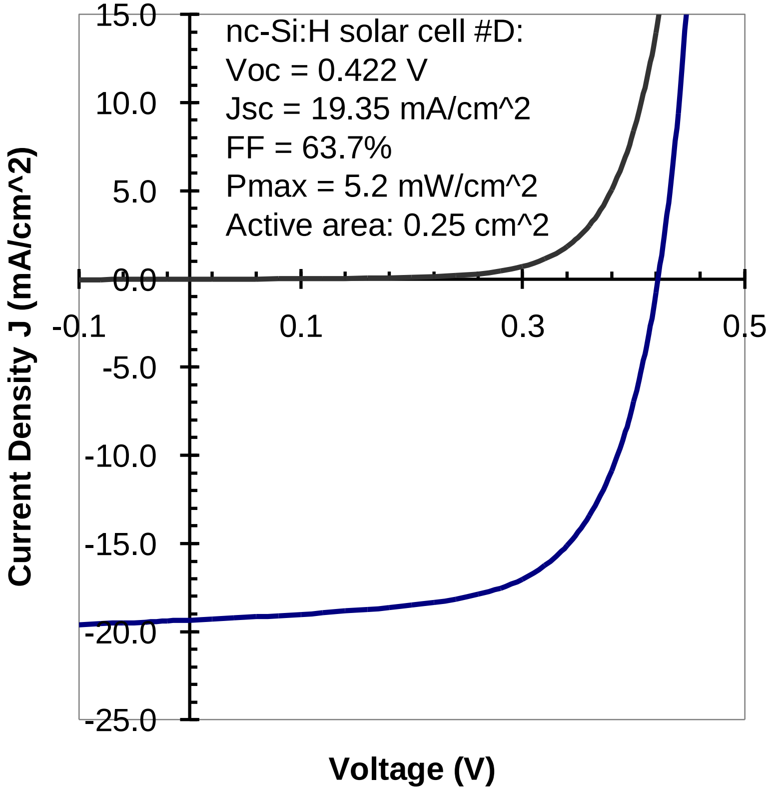
3. **Uniformity study of VHF deposition.**

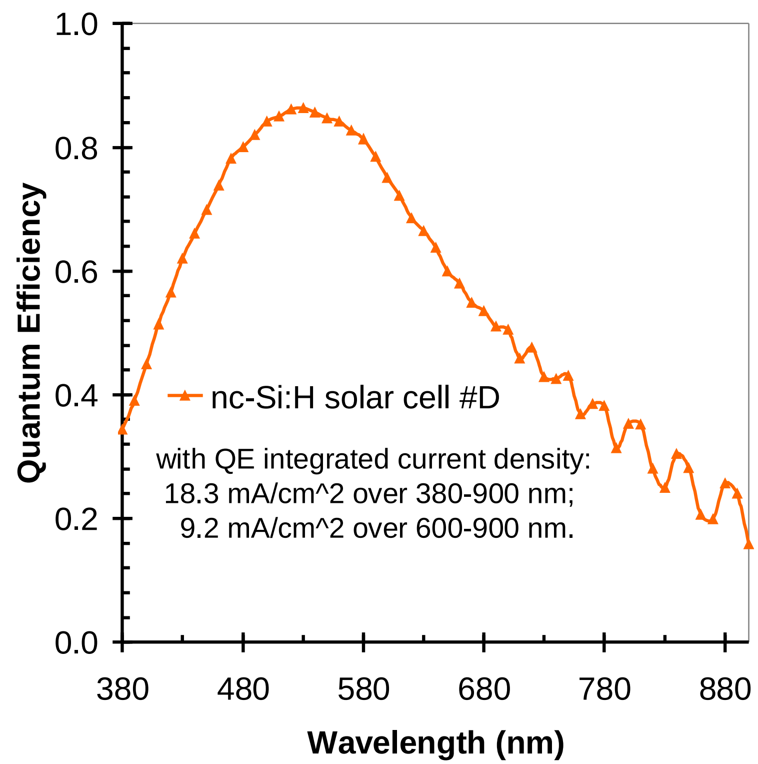
Deposition conditions nc-Si:H solar cells

- PECVD techniques using UT multi-chamber load-locked deposition system;
- Substrates: 10 cm x 10 cm stainless steel substrates coated with Ag/ZnO back reflectors;
- 15nm a-Si:H n-layer and 20 nm nc-Si:H p-layer were prepared using the conventional 13.56 MHz RF-PECVD technique at deposition rates near 1 Å/s.
- Deposition parameters for nc-Si:H i-layers:
  - VHF-PECVD technique with a frequency of 70 MHz and a power density of ~0.6 W/cm^2;
  - Substrate temperature T_{sub} in the range of 150 – 400 °C;
  - Gas mixtures of disilane/hydrogen with a grading gas mixture ratio [Si2H6/H2]: 1sccm/200sccm to 3sccm/200sccm;
  - nc-Si:H i-layers with thicknesses of up to 3200 nm and deposition rates of up to 6.0 Å/s.

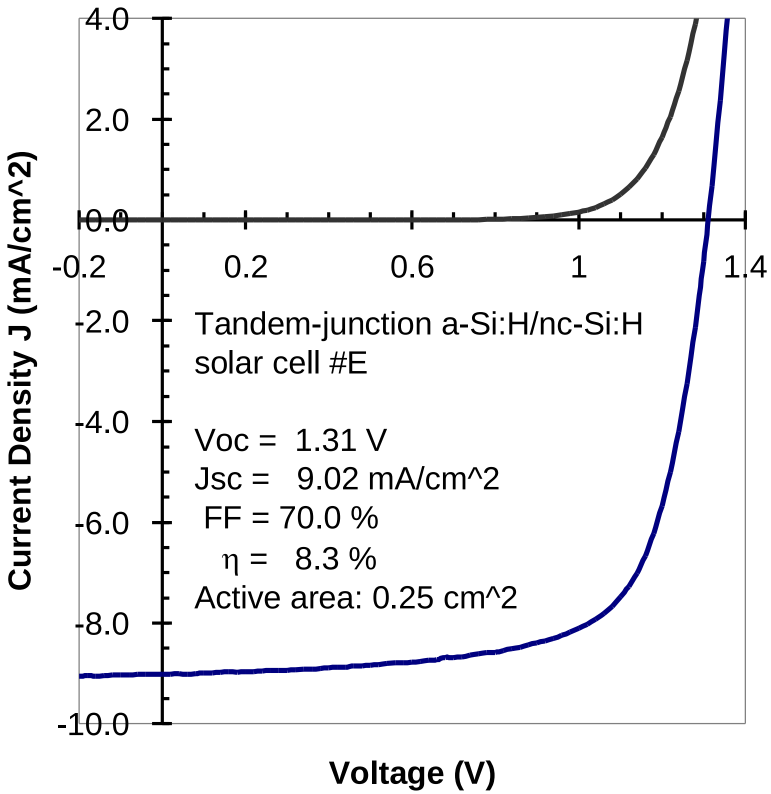
J-V characteristics and quantum efficiencies of nc-Si:H cells by VHF PECVD

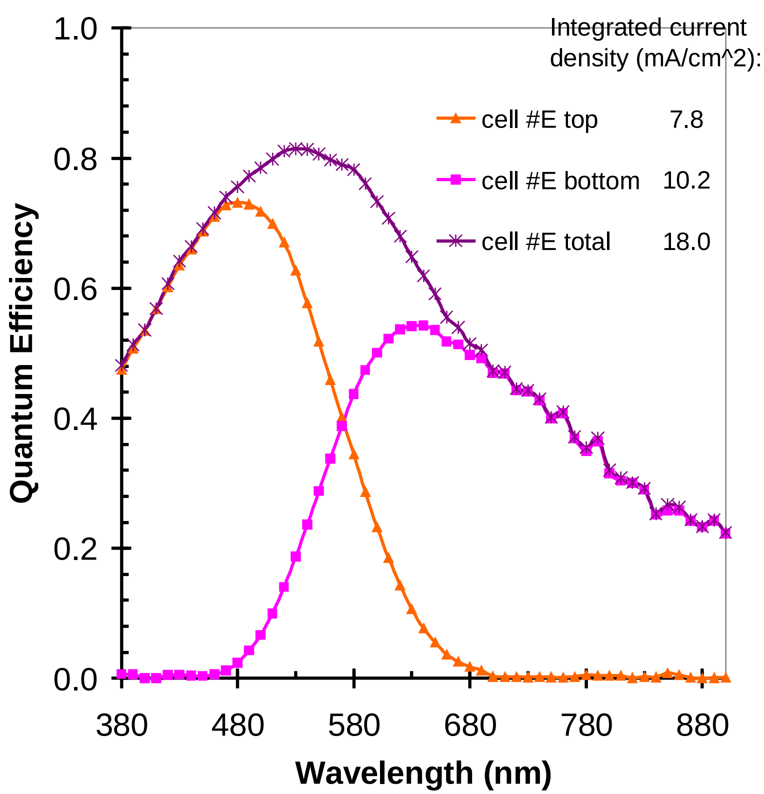
Single-junction nc-Si:H cell with i-layer of 2700 nm and $\eta = 5.2\%$ **prepared by VHF PECVD**



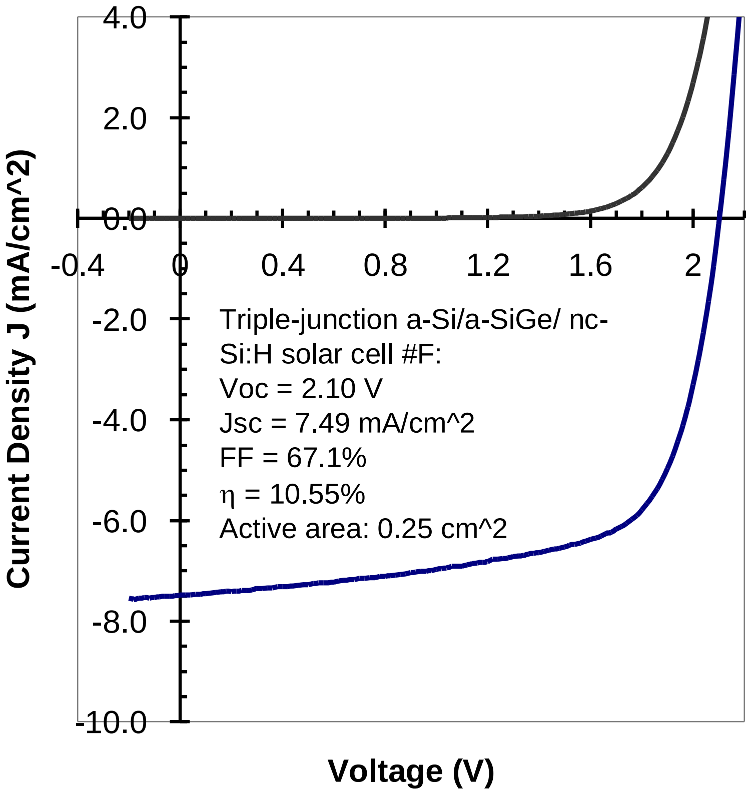


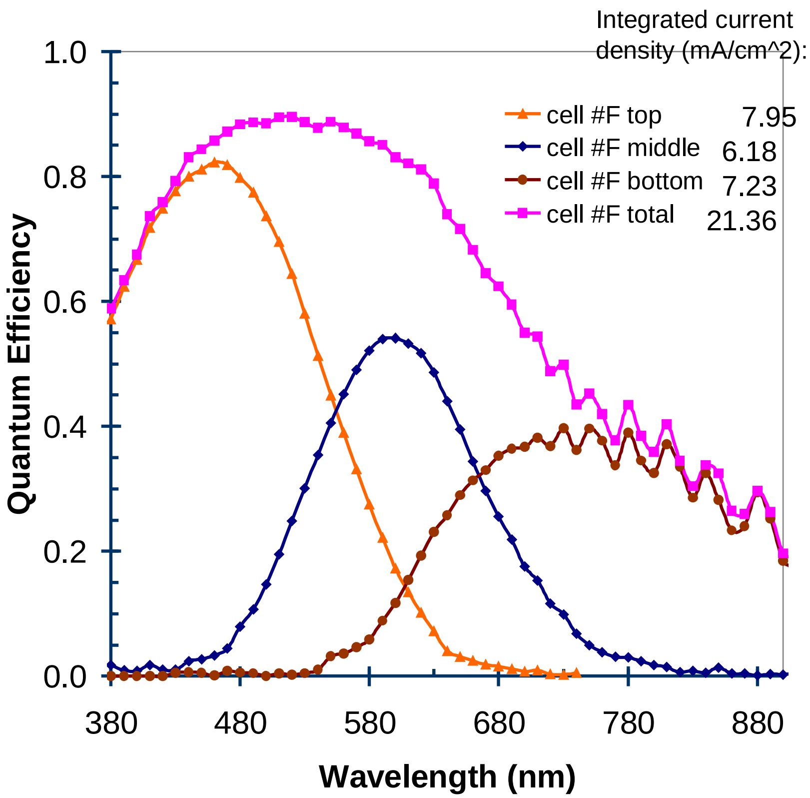
Tandem-junction solar cell with VHF nc-Si:H bottom-cell





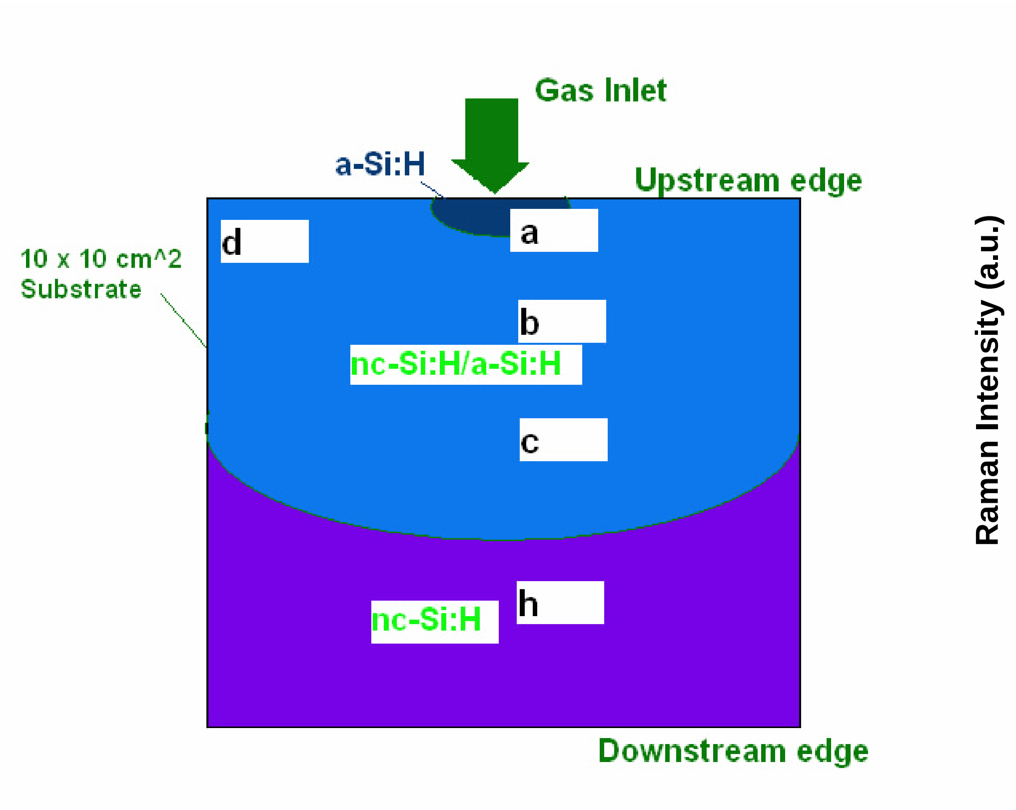
Triple-junction solar cell with VHF nc-Si:H bottom-cell

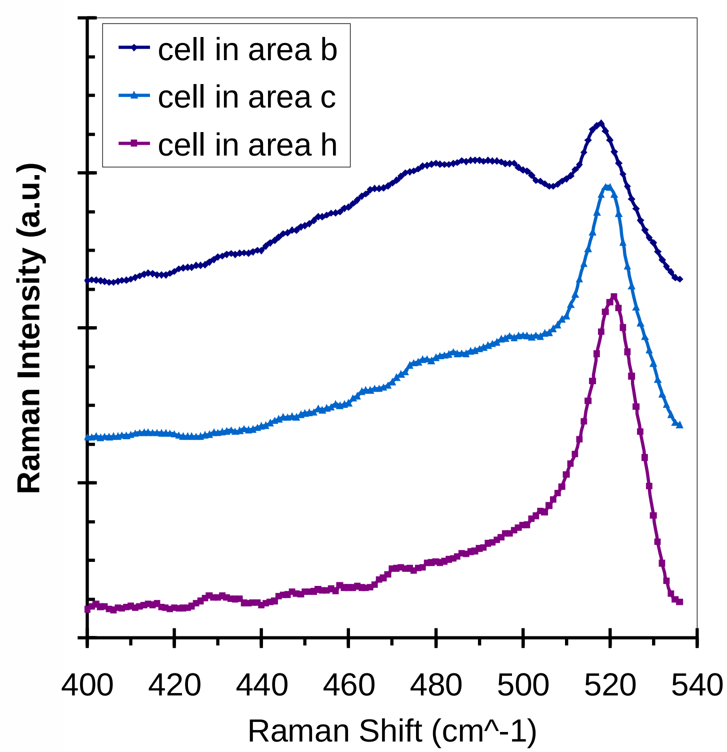




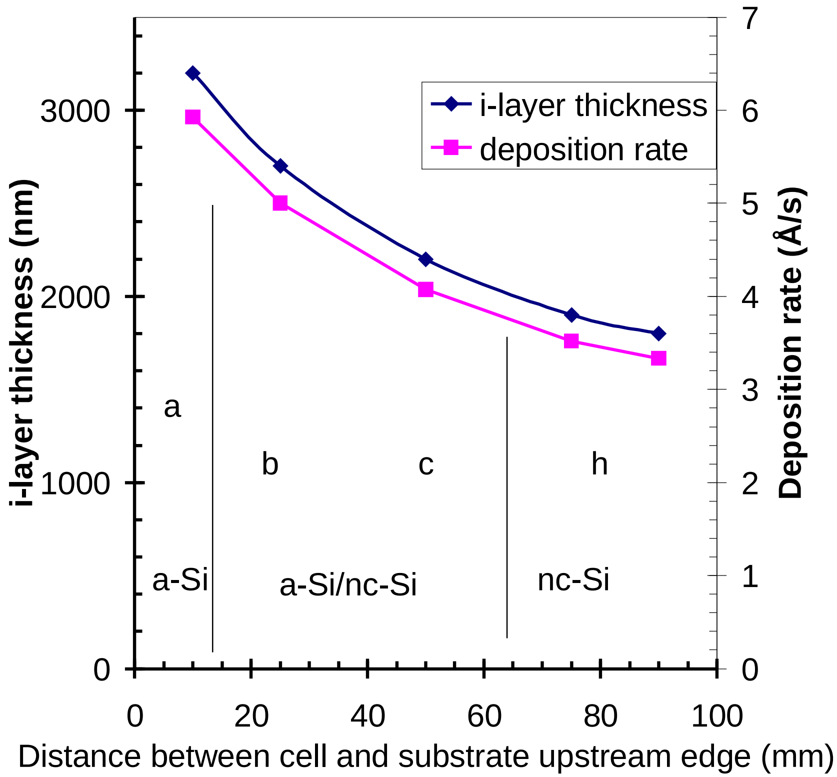
Uniformity study of VHF nc-Si:H i-layer deposition

- VHF nc-Si:H deposition with high rate by using UT RF-PECVD deposition chambers, which is used for routine fabrication of a-Si:H/a-SiGe:H/a-SiGe:H solar cells with a simple gas feeding structure, results in:
  - Variations of micro-structure phases within silicon i-layer across the 10 cm x 10 cm substrate; The nanocrystalline volume fractions within the silicon i-layers increase with increasing distance between cell and substrate upstream edge.



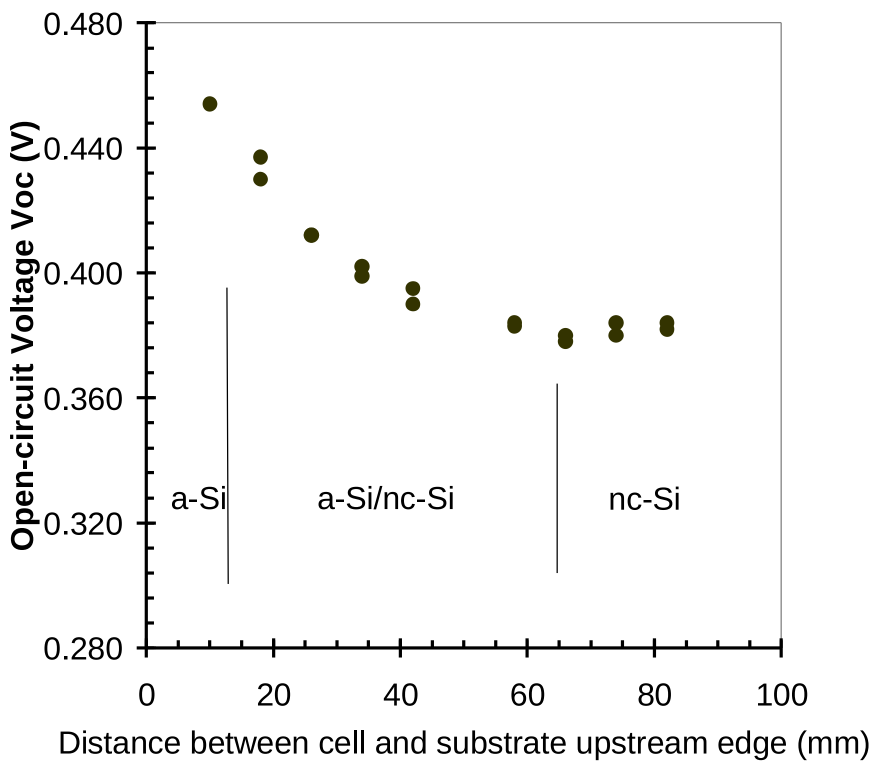


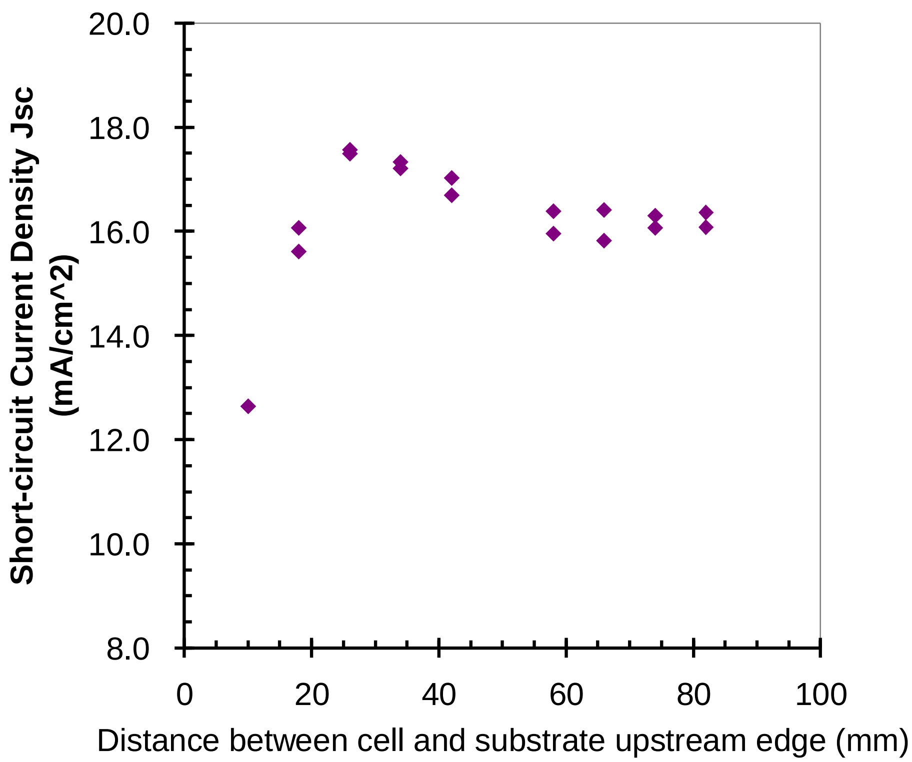
– Variations in film thickness and deposition rate across the 10 cm x 10 cm substrate;



The deposition rate with a value of 5.9 Å/s, which is related to a film thickness of 3200 nm, was highest at the upstream substrate area nearest the Gas Inlet, is gradually reduced to the lowest value of 3.3 Å/s at the downstream areas far from the Gas Inlet.

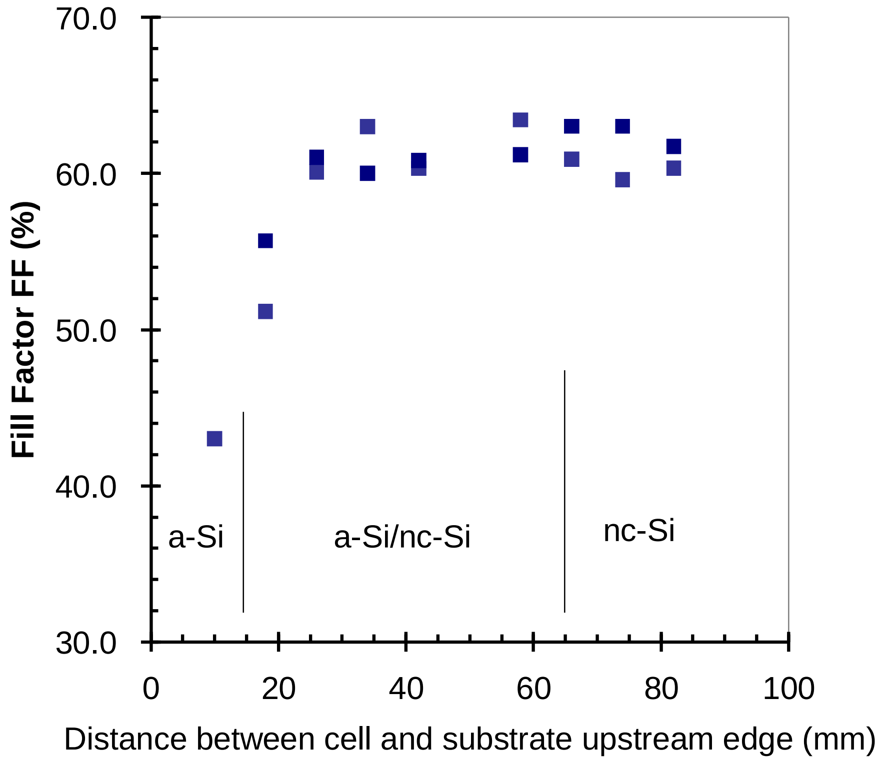
Device Uniformity of nc-Si:H Cells by VHF PECVD

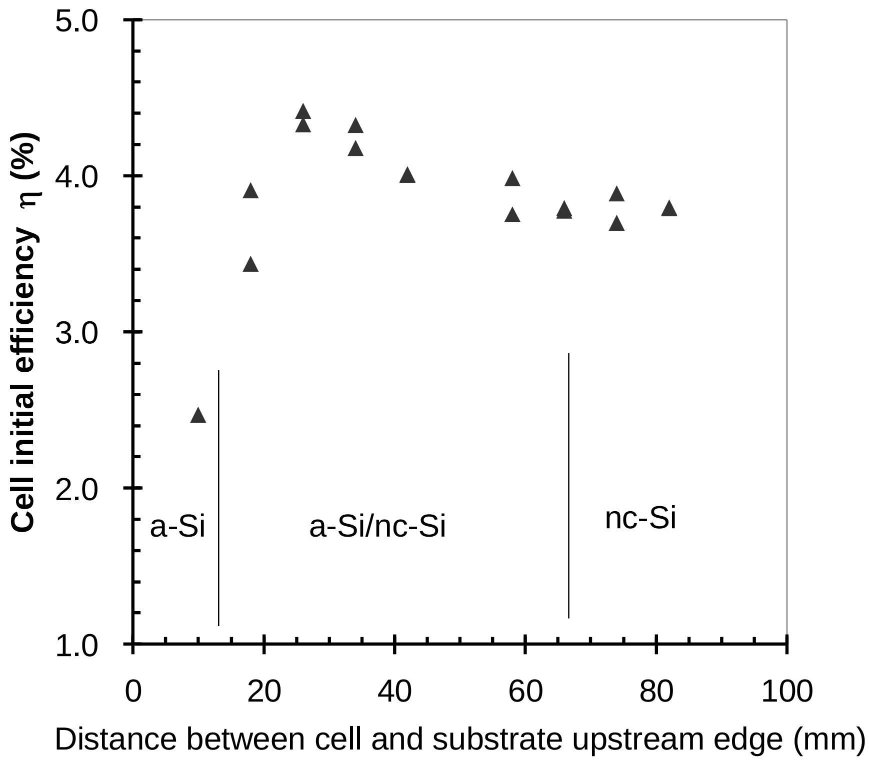




Variations in Voc: The decrease of Voc value reflects essentially the increase of the nanocrystalline volume fraction in the mixed materials within the intrinsic layers with increasing distance D.

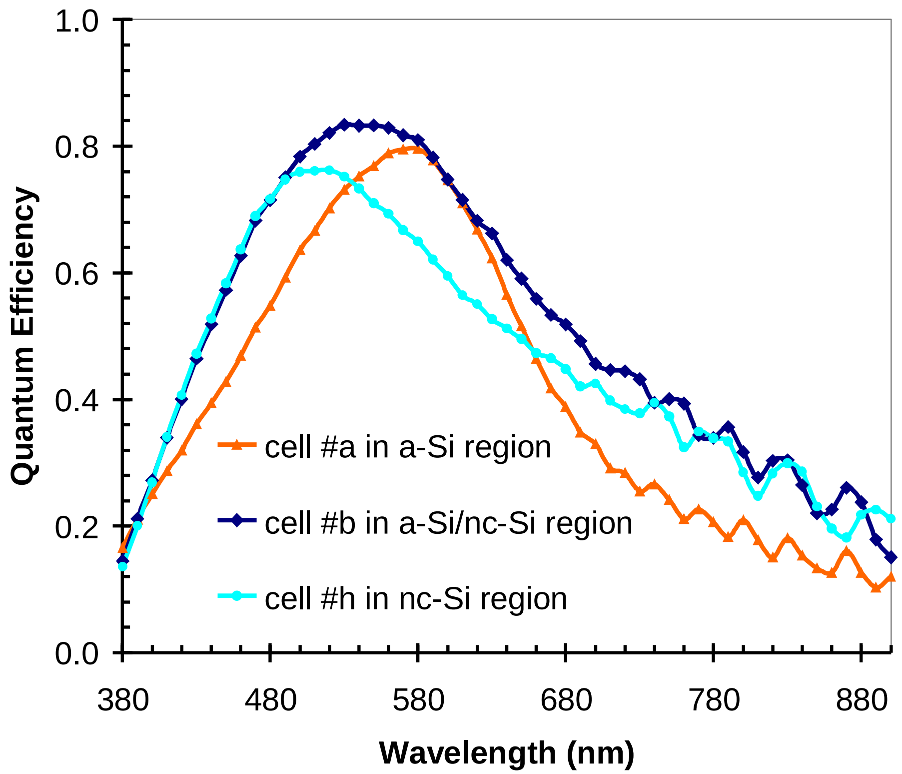
Variations in Jsc: Cells in a-Si/nc-Si region have the highest short-circuit current density.





Variations in FF: The fill factor FF increases dramatically from 43% in a-Si region to 62% in a-Si/nc-Si mixed phase region and is almost constant of a value around 62% in nc-Si region.

Variations in initial efficiency η : Cells in a-Si/nc-Si region have the highest efficiency. The cell in a-Si region has the lowest efficiency.



In comparison to the cell # a in a-Si region and the cell # h in nc-Si region, the cell # b, whose i-layer was grown at the transition region of nc-Si:H/a-Si:H mixed phase, has the best spectral response and the highest efficiency.

Cell #	D from upstream edge (mm)	i-layer thickness (nm)	Voc (mV)	Jsc (mA/cm^2)	QE integral current over 650-900nm (mA/cm^2)	FF (%)	Initial efficiency (%)
a	14	3200	454	12.6	4.26	43	2.5
b	30	2700	411	17.0	6.37	60	4.2
h	74	1800	375	16.1	5.83	61	3.7

Summary

- Preliminary effort on VHF nc-Si:H film depositions shows the uniformity of film thicknesses and micro-structure phases across the substrate are very sensitive to gas flow and hydrogen dilution.
- VHF nc-Si:H single-junction cell of η = 5.2%, tandem-junction solar cell of η = 8.3% and triple-junction cell of 10.55% have been obtained.
- VHF nc-Si:H solar cell prepared in a-Si/nc-Si phase transition region has the best efficiency.
- The laminar flow-type gas feeding structure used in UT RF-PECVD deposition chamber with rates less than 2 Å/s for route fabrication of a-Si:H based cells is not ideal for VHF nc-Si:H deposition at high rate.

→ ***A novel gas feeding scheme has been designed and installed in UT's multi-chamber PECVD system and is under demonstration.***

High Growth-rate nc-Si Cells Deposited at High Power & High Pressure Regime

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Experimental

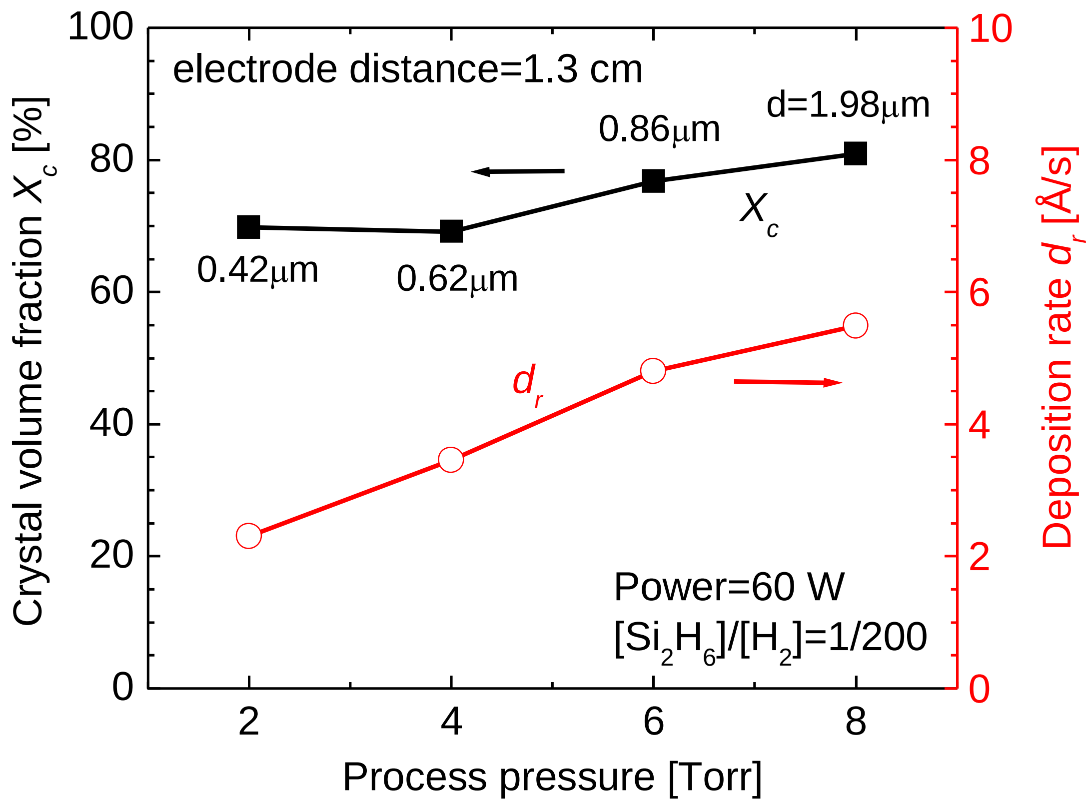
- **RF** power = 40 ~ 100 W (power density = 0.73 ~ 1.82 W/cm^2)
- High pressure = 2~ 8 Torr
- Electrode distance; 1.3 cm
- H_2 flow; constant (200sccm)
- Each film has approximately 1 μm.
- Deposited on glass, stainless steel, ECD supplied BR, UT-deposited BR
  - Cut to 1×1 inch. Some shadow masks insert, in order to prevent peeling off and make it easy to measure the film thickness.
- Film thickness; stylus profiler, transmittance
  - some sample has shadow mask
- Crystal volume fraction; Raman spectroscopy
- Data based on GD1366 – GD1406

Comment;

* c-Si wafer was used for FTIR, but almost every sample on the wafer peeled off.
(sometimes, even in case of glass and SS substrates, deposited films peeled off also.)

Process Pressure Dependency

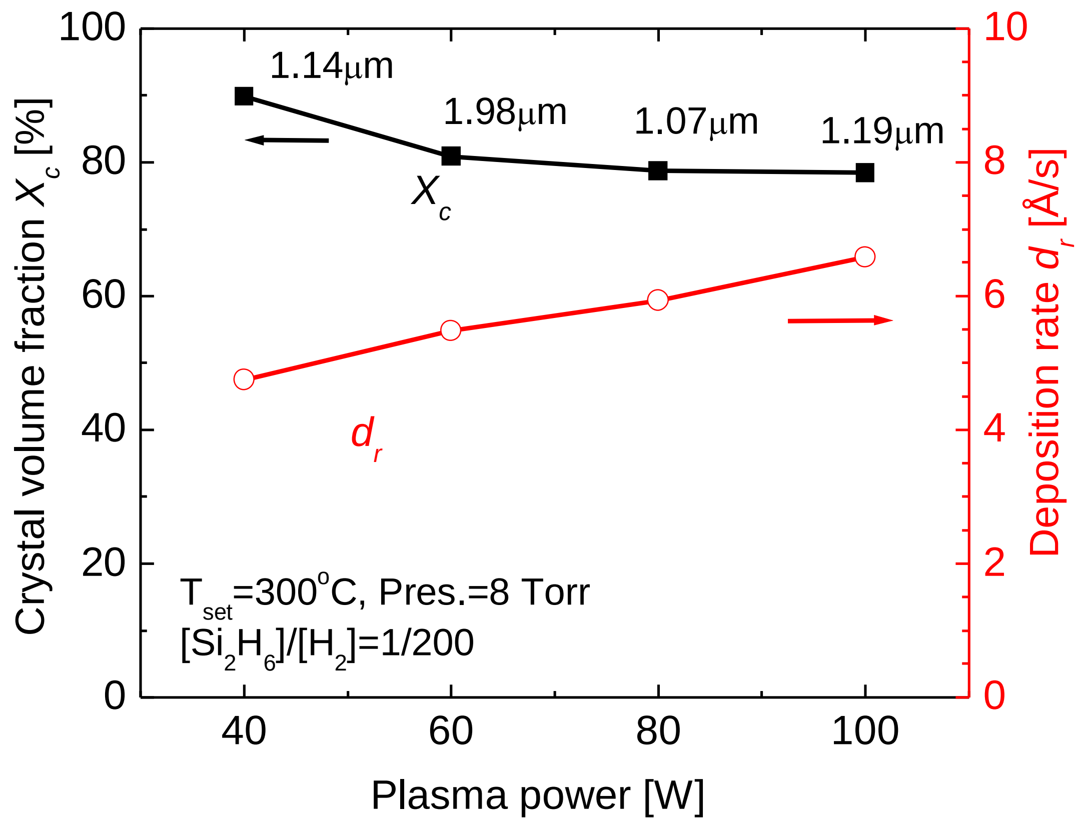
- Linear increase of depo-rate with increasing pressure
- Gradual increase of the crystallinity, X_c (from Raman)
  $X_c=(I_{520}+I_{510})/(I_{520}+I_{510}+I_{480})$
  - I_{520}; integrated intensity at 520 cm^{-1} (crystal phase)
  - I_{510}; integrated intensity at 510 cm^{-1} (grain boundaries and/or strain Si-Si phase *etc.*)
  - I_{480}; integrated intensity at 480 cm^{-1} (amorphous phase)
- 8 Torr →optimized pressure in our current system (electrode distance=1.3 cm)



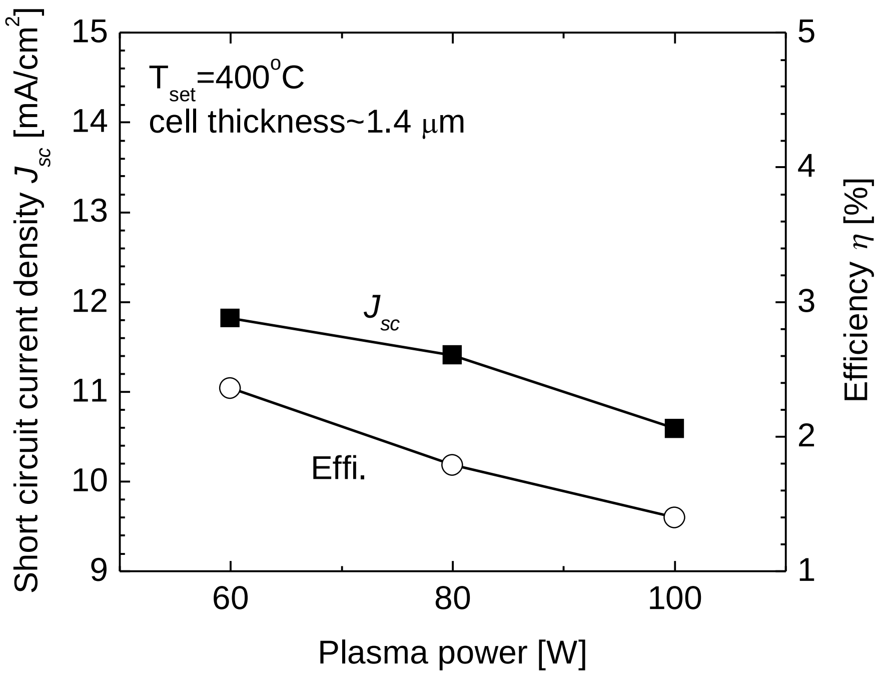
Plasma Power Dependency - film

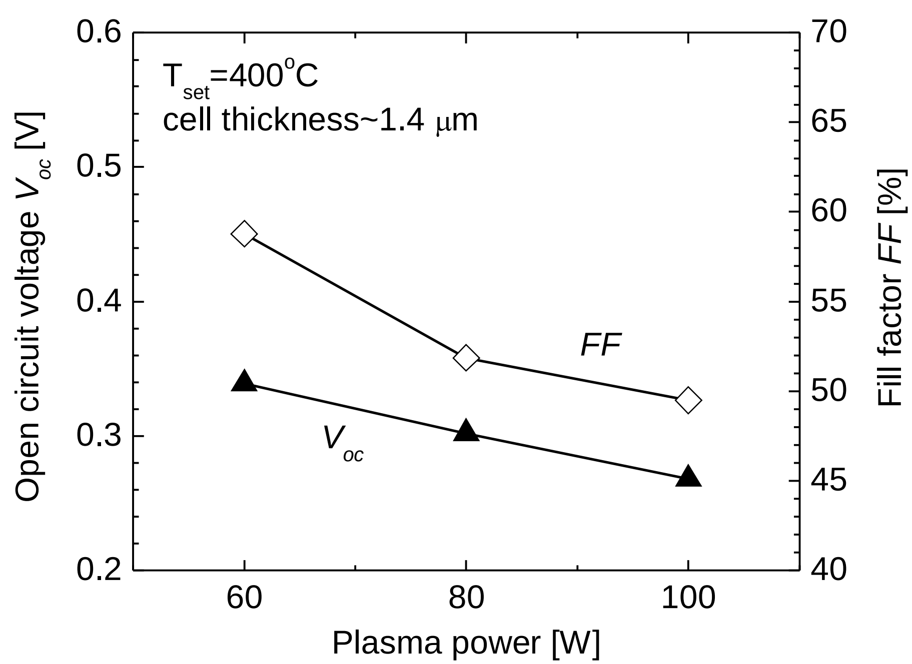
- No strong effect on depo-rate with increasing power at this gas flow
- Higher power region, almost constant crystallinity X_c
- Powder formation on chamber wall while less powder on samples

→ Using these condition, solar cells were fabricated
  - nip-sequence
  - ITO front contact
  - Thickness~1.4 μm



Plasma Power Dependency – cell





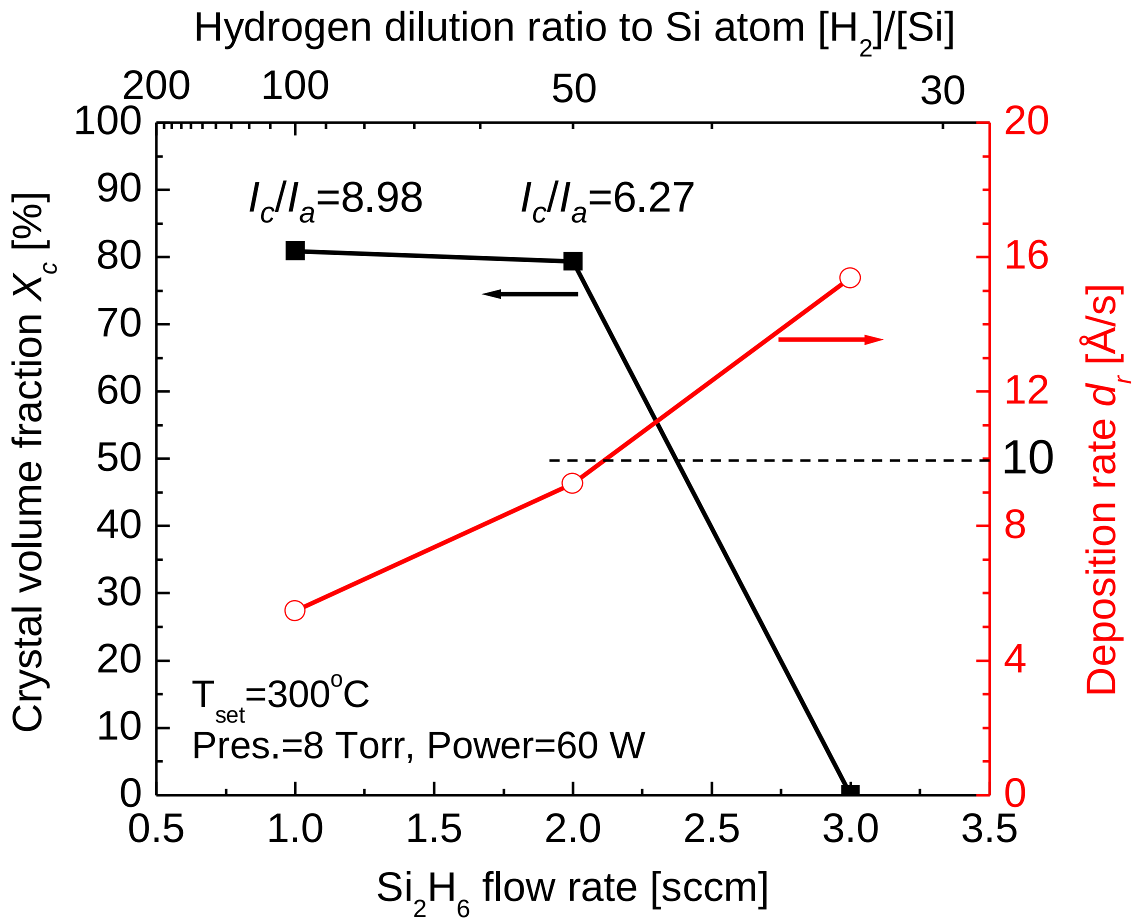
- Every cell performance; monotonical decrease in η with increasing plasma power
- Cell efficiency still low, possibly due to crystallinity being too high

→ Another option … change of Si_2H_6 flow rate

Disilane Flow Rate Dependency

- Significant increase in depo-rate with increasing flow rate
- Reached around 10 Å/s (Si_2H_6/H_2=2/200) while still nc-Si
- Between 2 and 3 sccm of Si_2H_6 flow, nc-Si to a-Si transition occurs.
- I_c/I_a ratio decreased while the crystallinity remains unchanged at ~80%

→contains much grain boundaries and void.



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Summary

- nc-Si films and solar cells are deposited at high rate (~10A/s) using RF PECVD at high pressure (8Torr), high RF power (0.7~1.8 W/cm^2) and high H dilution (Si_2H_6/H_2=2/200)
- Process pressure of 8 Torr is appropriate for nc-Si deposition for electrode distance of 1.3 cm
- Excessive high plasma power, with sufficient H dilution leads to poorer device performance.

Graded Hydrogen Dilution Profile for i-layer on nc-Si Cells

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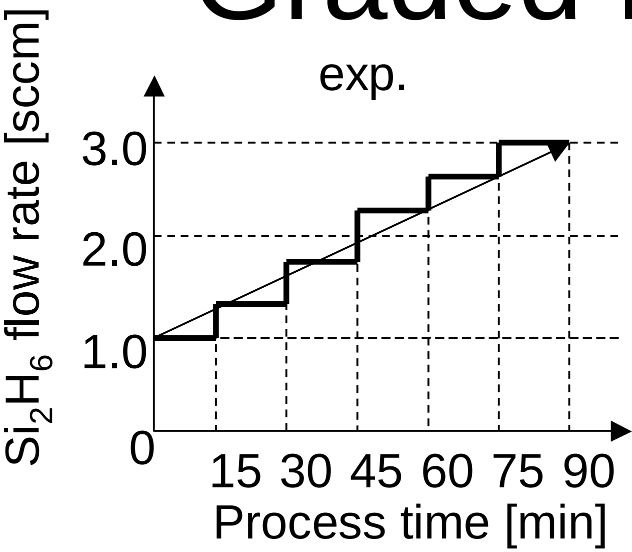
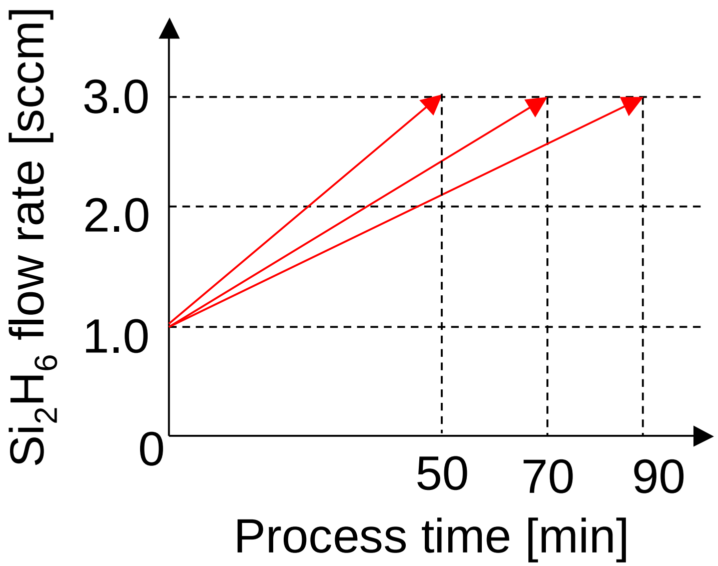
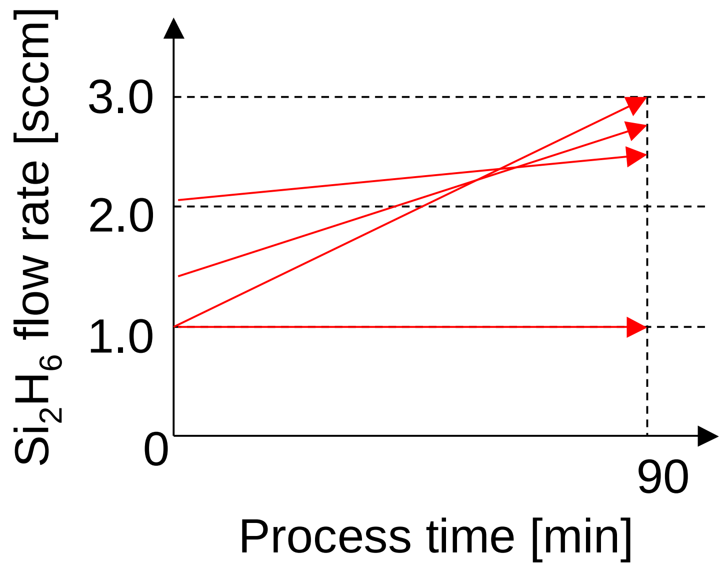
Graded Dilution Profile



- Step profile is used.
- Gradual increase the Si_2H_6 flow rate.
- H_2 flow rate keep constant (=200 sccm).
- i-layer; T_{set}=400^{o}C, 70 W (70 MHz), 0.35 Torr
- n-layer; std. a-Si condition
- p-layer; nc-Si condition
- extracted data point is "_4, best 3 efficiency" and point "33" well agree with that result.
- Data based on GD1281 – GD1346

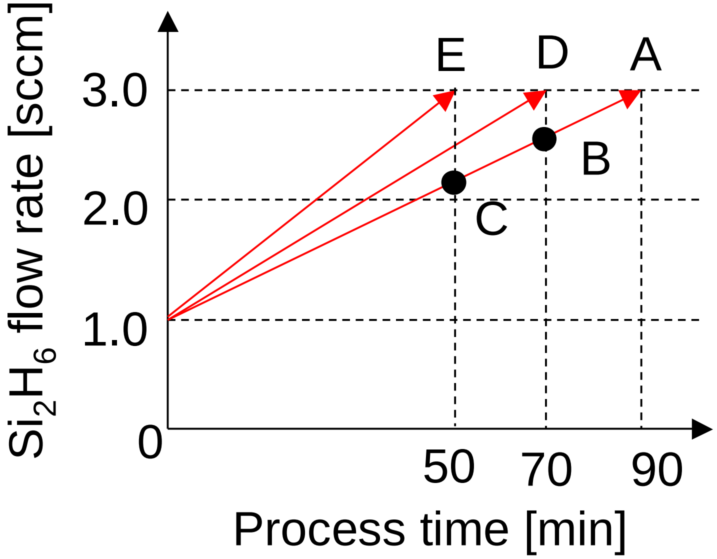


Time-dependence series



slope-dependence series

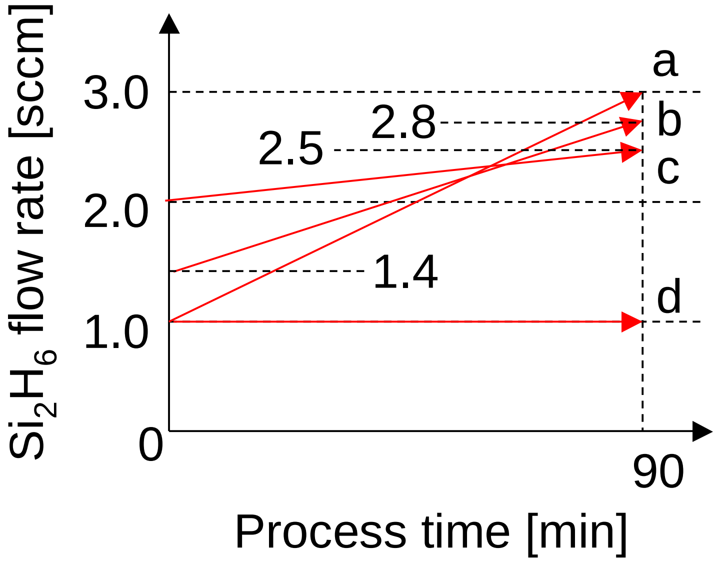
Time-Dependence Series



	J_{sc}[mA /cm^2]	V_{oc} [V]	FF [%]	Eff. [%]	Sample #
A	19.24	0.421	62.2	5.04	GD1281
B	16.28	0.356	62.6	3.62	GD1326
C	16.46	0.379	64.8	4.04	GD1327
D	20.42	0.380	61.2	4.75	GD1310
E	20.48	0.388	61.6	4.89	GD1324

- A-B-C series → systematic increase of *FF* and decrease of J_{sc} observbed with decreasing i-layer thickness
- A-D-E series → Increase of J_{sc} observed with reducing process time, but V_{oc} decreases

Slope-Dependence Series



	J_{sc}[mA/cm^2]	V_{oc} [V]	FF [%]	Eff. [%]	Sample #
a	19.24	0.421	62.2	5.04	GD1281
b	16.02	0.380	58.3	3.55	GD1337
c	15.61	0.385	56.7	3.41	GD1340
d	14.04	0.336	54.6	2.58	GD1328

- Constant at 1 sccm (d) → low cell performance
  → crystallinity being too high
- a-b-c series → decreasing slope enhances a-Si phase in the film.
  → However, V_{oc} is not improved, instead, it is decreased.
  → Systematic explanation needs more data.

Summary

- Graded hydrogen dilution profile can be used to achieve constant microcrystalinity in mixed phase of amorphous and nanocrystalline, desirable for high nc-Si cell efficiency
- nc-Si cell performance depends sensitively on the grading slope of hydrogen dilution profile
- Further study is required to draw definitive conclusion.